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INNER ZONE ENERGETIC ELECTRON REPOPULATION BY RADIAL DIFFUSION

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72 MAY 22

Laboratory Operations
THE AEROSPACE CORPORATION

Prepared for SPACE AND MISSILE SYSTEMS ORGANIZATION
AIR FORCE SYSTEMS COMMAND
LOS ANGELES AIR FORCE STATION
Los Angeles, California

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FOREWORD

This report is published by The Aerospace Corporation, El Segundo, California, under Air Force Contract No. F04701-71-C-0172.

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Approved

George Paulikas

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Project Officer

Abstract

A quantitative study of the intrusion of natural electrons into the inner radiation zone during and after the geomagnetic storm of September 2, 1966 shows that the transport is consistent with a radial diffusion mechanism in which the first two invariants are conserved. Except for the three day period of the storm main phase when data were missing, the radial diffusion coefficient is $D = 2.7 \times 10^{-5} L^{7.9} \mu^{-0.5}$ day^{-1}, in the range $1.7 \leq L \leq 2.6$ and $13.3 \leq \mu \leq 27.4$ Mev gauss^{-1}. This value could be produced by variation of a large-scale electric field across the magnetosphere having an amplitude of 0.28 mv per meter and a period of 1600 seconds. Electric fields having approximately these characteristics have been inferred from previous observations of the motion of whistler ducts within the plasmapause. If fields of this amplitude and period exist throughout the magnetosphere, the radial diffusion of all geomagnetically trapped particles except the high energy inner zone protons is strongly influenced by electric field variations. A comprehensive review of previously reported radial diffusion coefficients shows reasonable agreement for L less than about 3.0, but serious discrepancies among reported values exist for determinations made in the outer zone. These discrepancies cannot be explained by the simple theory of radial diffusion due to variation of large-scale electric or magnetic fields.

CONTENTS

FIGURES

1. Introduction

The identification of the important source, transport, and loss mechanisms for energetic trapped electrons is made difficult by the fact that several mechanisms operate simultaneously at most times. Under these conditions the time history of the electron distribution may not reveal the underlying physical processes. From time to time the distribution is altered in such a way that a single mechanism temporarily dominates the time variation of the distribution. Such events permit quantitative evaluation of various hypothetical mechanisms. Notable examples of these events include the Starfish addition, whose study demonstrated the importance of atmospheric scattering at low altitudes and the very long pitch angle diffusion lifetimes at the maximum of the inner zone (Van Allen, 1966); the nuclear injection of November 1, 1962, from which unambiguous determinations of pitch angle diffusion lifetimes and radial diffusion coefficients were made (Newkirk and Walt, 1968); the magnetic storms of 1965 from which electron acceleration within the magnetosphere was demonstrated (Williams et al., 1968); and the injection of December 20-29, 1962, from which outer-zone radial diffusion coefficients could be calculated (Newkirk and Walt, 1968; Lanzerotti et al., 1970).

Another such event has been selected in this study: the first observed natural intrusion of electrons into the inner zone after the Starfish explosion. It has been used to determine an appropriate radial diffusion coefficient before and after the magnetic storm which caused the intrusion.

The computation of such a coefficient does not demonstrate the existence of the mechanism of radial diffusion. The mechanism depends upon magnetic and electric field variations for which there is yet only limited experimental evidence. The events in the radiation belt which have permitted calculations of radial diffusion coefficients have involved particles in various locations at different times having different first invariant values. The resulting coefficients which have been reported in the literature have shown so little resemblance to each other as to cast doubt on the physical reality of the assumed diffusion mechanism. It is shown in this work that suitable comparison between the reported values and relatively simple theoretical predictions previously published reduces these apparent discrepancies substantially, thereby strengthening the case for the physical existence of the radial diffusion mechanism and the appropriateness of the transport equation which has been used to describe it.

2. Geomagnetic Storm and Inner Zone Electron Injection

The geomagnetic storm of September 2, 1966 (day 245) was a moderately intense storm with a sudden commencement at about 0830 UT and a main phase decrease starting the next day at about 0600 UT. The hourly D_{st} values for days 240 through 249 are shown in Figure 1. The storm was preceded by other storms, the most intense of which was on day 242, with a sudden commencement at 1112 UT. The A_p indices included in Figure 3 indicate that

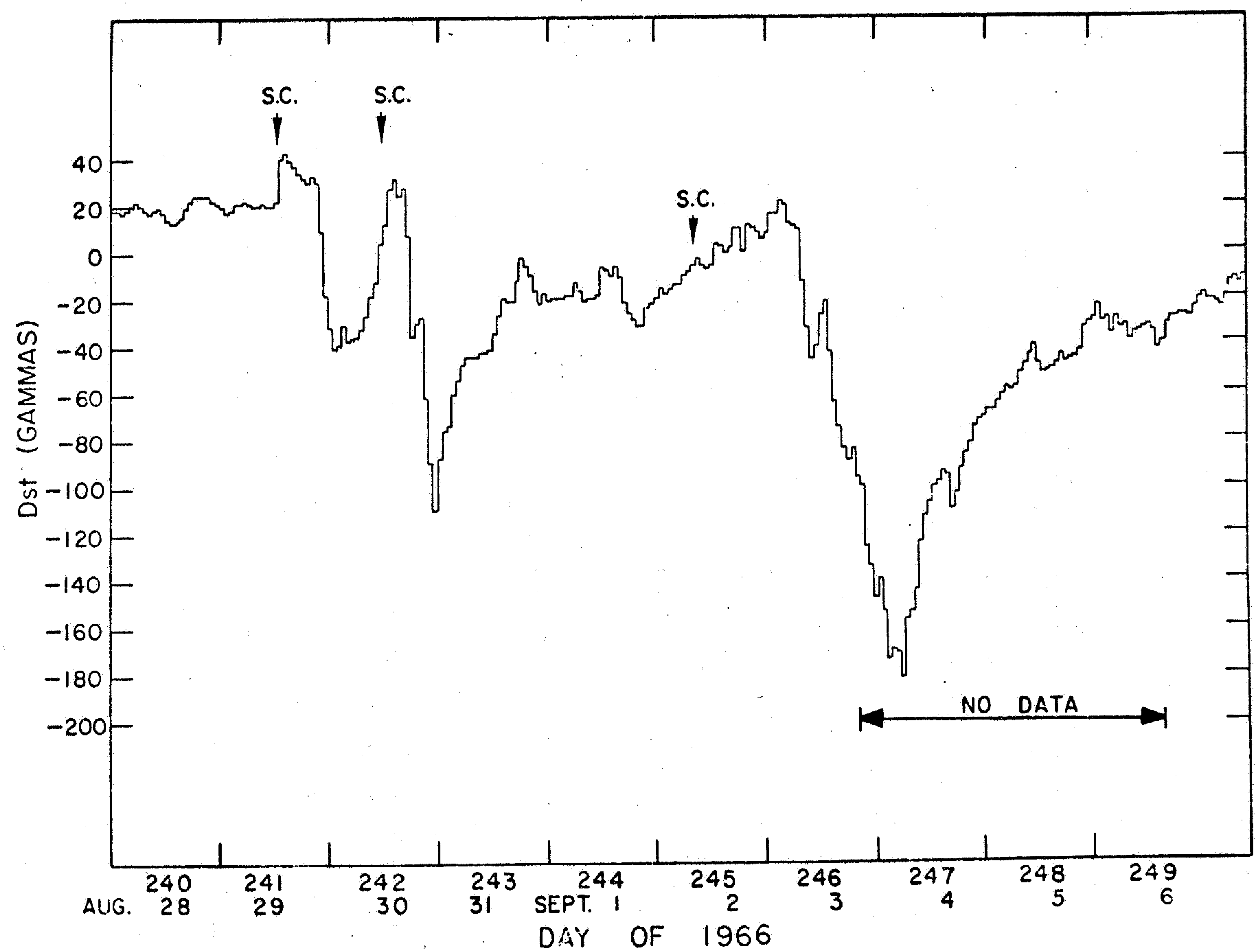

Figure 1. D_{st} Values from Day 240 through Day 249, 1966

the entire period from day 242 to day 253 was relatively disturbed.

The effect of this geomagnetic storm on the electron population of the inner zone has previously been reported by Pfitzer and Winckler (1968). They observed gradual increases in the intensity of electrons of energy 50<E<690 kev at L values below 1.8 after the storm. They concluded that the apparent inward diffusion of these electrons was responsible for replenishment of the inner radiation belt, creating a new and relatively stable electron population. They estimated that one or two storms of such intensity per year would be sufficient to supply the inner zone electrons.

The present paper is a quantitative study of the same event using electron data from another satellite.

3. Radial Diffusion Equation and Solution

For a diffusion process which violates only the third adiabatic invariant, the time dependent radial diffusion equation for the electron distribution function f is (Newkirk and Walt, 1968)

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial L} \left[\frac{D}{L^2} \frac{\partial}{\partial L}(fL^2) \right] - \frac{f}{\tau} \qquad (1)$$

The quantity $f(\mu,J,L,t)\, d\mu dJ dL$ is the number of electrons in the element $d\mu dJ dL$; μ and J are the first and second adiabatic invariants of the trapped electron motion respectively, and L is the McIlwain spatial coordinate. For equatorially trapped electrons J=0 and the first invariant μ is obtained from the relation

$$\mu = (1/2B_o)\ (T/m_o c^2)\ (T+2\ m_o c^2)$$

where T is the electron kinetic energy, B_o is the equatorial field value, and $m_o c^2$ is the rest mass energy. Equation 1 is strictly applicable only in a dipole field. The distribution function is obtained from the measured equatorial unidirectional differential electron intensity $j_\perp$ by the relation (Farley and Walt, 1971)

$$L^2 f = 2\pi^2 \mu^{-1} L^3 j_\perp \qquad (2)$$

Use of the pitch angle diffusion loss term $f\tau^{-1}$ implies that the pitch angle distribution is always in its lowest eigenmode, characterized by an exponential decay lifetime.

The result of performing the indicated differentiation of the radial diffusion term and integrating the equation with respect to time from t_1 to t_2 is

$$\int_{t_1}^{t_2} \frac{\partial f}{\partial t}\, dt = \int_{t_1}^{t_2} D\frac{\partial}{\partial L}\left[\frac{1}{L^2}\,\frac{\partial(fL^2)}{\partial L}\right] dt + \int_{t_1}^{t_2} \frac{\partial D}{\partial L}\left[\frac{1}{L^2}\,\frac{\partial(fL^2)}{\partial L}\right] dt - \int_{t_1}^{t_2} \frac{f}{\tau}dt$$

If the time intervals are chosen sufficiently short that D, $\frac{\partial D}{\partial L}$ and τ do not change between t_1 and t_2, the equation may be written

$$\int_{t_1}^{t_2} \frac{\partial f}{\partial t}\, dt = D\int_{t_1}^{t_2} \frac{\partial}{\partial L}\left[\frac{1}{L^2}\,\frac{\partial(fL^2)}{\partial L}\right] dt + \frac{\partial D}{\partial L}\int_{t_1}^{t_2} \frac{1}{L^2}\,\frac{\partial(fL^2)}{\partial L} dt - \frac{1}{\tau}\int_{t_1}^{t_2} f dt$$

This operation reduces the differential equation to an algebraic equation in three variables — D, its derivative $\frac{\partial D}{\partial L}$, and τ.

It has been assumed that the radial diffusion coefficient varies as $L^m\mu^n$ so that $\frac{\partial D}{\partial L}$ becomes proportional to $mL^{m-1}\mu^n$ and

$$\int_{t_1}^{t_2} \frac{\partial f}{\partial t}\, dt = D\int_{t_1}^{t_2} \left\{\frac{\partial}{\partial L}\,\frac{1}{L^2}\,\frac{\partial(fL^2)}{\partial L} + \frac{m}{L^3}\,\frac{\partial(fL^2)}{\partial L}\right\} dt - \frac{1}{\tau}\int_{t_1}^{t_2} f dt \tag{3}$$

D may now be determined by numerical integrations for a time interval t_1 to t_2 in which the distribution function f, its derivative with respect to time, and its first and second derivatives with respect to L are known.

4. Data

The electron data used in this study were obtained by a magnetic spectrometer on the OV3-3 (1966-70A) satellite, launched on August 4, 1966. The satellite perigee, apogee, inclination, and period were 362 km, 4488 km, 81.6^{o}, and 137 min respectively. The magnetic spectrometer measured the unidirectional electron intensity in nine differential energy channels with center energies between 300 and 2310 kev. A detailed description of this instrument has been presented previously (Vampola, 1969).

The eight weeks of data used in this paper have been selected from a 14 month study which includes about 750 passes through the inner zone. During this longer period, the data were systematically reduced by averaging the unidirectional intensity in each energy channel at local pitch angles of 90^{o} ($j_{\perp}$) over intervals of .01 in L and 0.1 in B/B_o, where B is the local field value and B_o is the equatorial field value at that L. These averages were used to construct distributions of $j_{\perp}$ versus B/B_o (equivalent to pitch angle distributions) for each energy at each L value. Within the energy range of this experiment, the energy spectrum was found to be independent of pitch angle.

During the eight week period including the large magnetic storm of September, 1966, one or two complete orbits of tape-recorded data were received from the satellite each day except on weekends. The analysis of the present paper requires as input data the unidirectional differential intensity of electrons at an equatorial pitch angle of 90°. Because the OV3-3 satellite does not reach the geomagnetic equator at L values above 2.0, and because it is desirable to take advantage of the large number of available off-equatorial measurements to obtain superior time resolution, the intensity at an equatorial pitch angle of 90° has been estimated from the data taken at smaller equatorial pitch angles in the following way.

For the interval $1.7 \leq L \leq 2.0$, $j_{\perp}(B/B_o=1)$ has been estimated from each measurement of $j_{\perp}(B/B_o)$ on these L shells from a consideration of the normal pitch angle distributions observed during the 14 month period. For the interval $2.1 \leq L \leq 2.8$, in which the OV3-3 satellite never reaches the geomagnetic equator, both the OV3-3 data and that of other experiments at and near the equator have been considered, and it has been determined that a reasonable estimate of $j_{\perp}(B/B_o=1)$ may be made by multiplying $j_{\perp}(B/B_o)$ by B/B_o. That is, the normal distribution of $j_{\perp}(B/B_o)$ has been taken to be inversly proportional to B/B_o. Data taken at values of B greater than 0.2 gauss were not used. Therefore, for L values ≤ 2.0, B/B_o was as large as 5.3, and for $2.1 \leq L \leq 2.8$ was as large as 14.1.

The equatorial estimates of $j_{\perp}$ were used to construct the required function $L^3 j_{\perp}$ ($\sim L^2 f$) at constant μ. This function was constructed for μ values of 13.3, 17.3, 22.0 and 27.4 Mev gauss^{-1}. Values for this function require

$j_\perp$ at a different energy for each L. The values were obtained by logarithmic interpolation from the nine-point differential energy spectrum determined from the measurements at each L.

Figure 2 displays two examples of $L^3 j_\perp$ at constant μ plotted against L at a particular time, and Figure 3 displays two examples of $L^3 j_\perp$ at constant μ plotted versus time at a particular value of L. Figure 3 illustrates an important characteristic of the data at all L and μ values: nothing dramatic occurs in connection with the sudden commencement or with the start of the main phase decrease. At the lower values of L ($L \lesssim 2.2$) the intensity is slowly increasing or decreasing, depending on the first invariant value. Above L of 2.2 the intensity is increasing at all first invariant values, possibly because of the effects of the earlier storm on day 242. At all values of L above 1.7 a large increase in intensity takes place in the period of no data extending from day 246.8 to day 249.6. The increases are progressively larger at larger L. Figures given by Vampola, 1971 illustrate these changes qualitatively in more detail than is given here.

In addition to the functions illustrated in Figures 2 and 3, the first and second derivatives of $L^3 j_\perp$ with respect to L are required for all times. These derivatives were obtained by fitting the data of Figure 2, differentiating numerically twice, and plotting and smoothing the result as a function of time. These functions also change significantly during the period of no data. The resulting body of data was used as the input to equation 3.

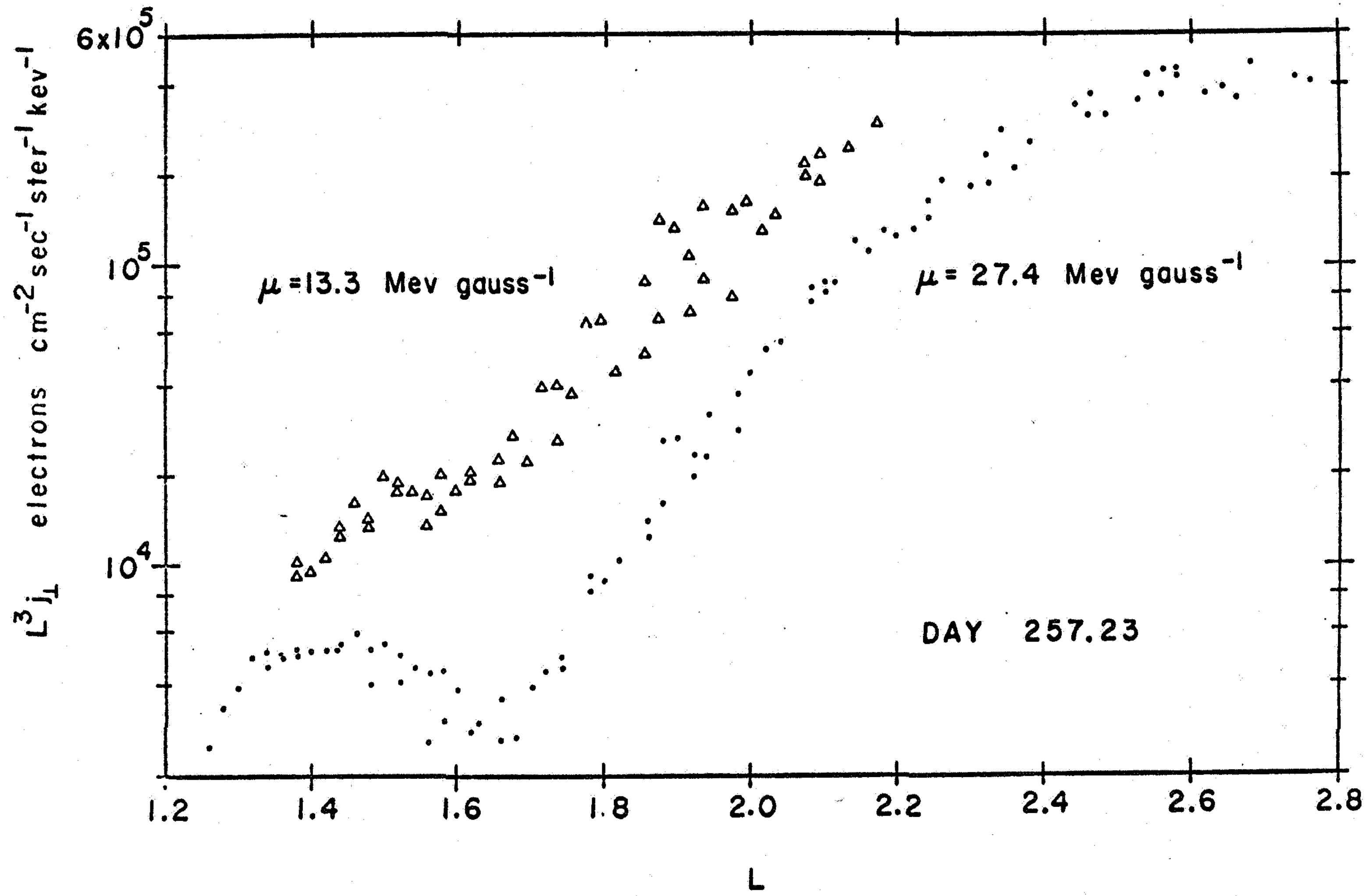

Figure 2. Two Representative Examples of the L Variation of $L^3 j_\perp$ at Fixed Time and First Invariant

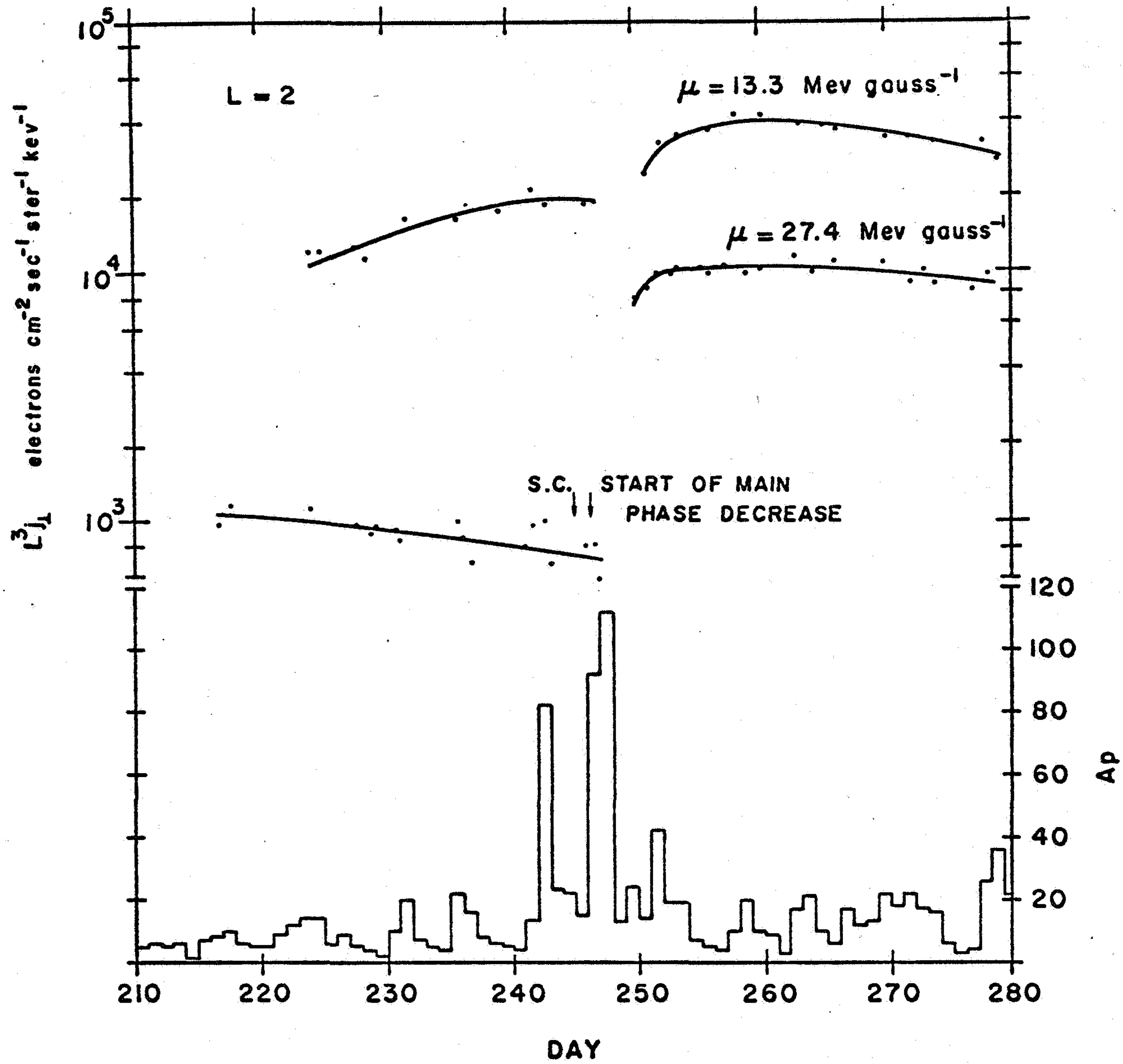

Figure 3. Two Representative Examples of the Time Variation of $L^3 j_\perp$ at Fixed L and First Invariant, and the Corresponding Values of A_p

The reported electron pitch angle lifetime in this region is a strong function of L. This behavior has been given theoretical justification by Lyons et al. (1971), who have predicted pitch angle lifetimes resulting from wave-particle interactions in this L interval. A number of the reported values of the pitch angle lifetime in the L range of interest are shown in Figure 4. In general, these estimates have considerable uncertainty because of the difficulty in separating the effect of pitch angle diffusion loss from other source, loss, and transport mechanisms which may be simultaneously affecting the electron distribution. Since any error in the choice of τ will affect the calculated values of D in this paper, the effect of uncertainty in τ has been explicitly carried through the calculation. The values of τ used in this paper are indicated by the curve in Figure 4. Calculations of D have also been made in every case with a value of τ larger by a factor of 1.5 and smaller by a factor of 1.5. Each value of D has been assigned a systematic error bar extending between the values of D resulting from the assumed extremes of τ. The theoretical values of Lyons et al. (1971) are more nearly 10 days than the value of 15 used above L of 2.1. If their values are correct, then the best values of D will be represented by the end of the error bars corresponding to a shorter choice of τ.

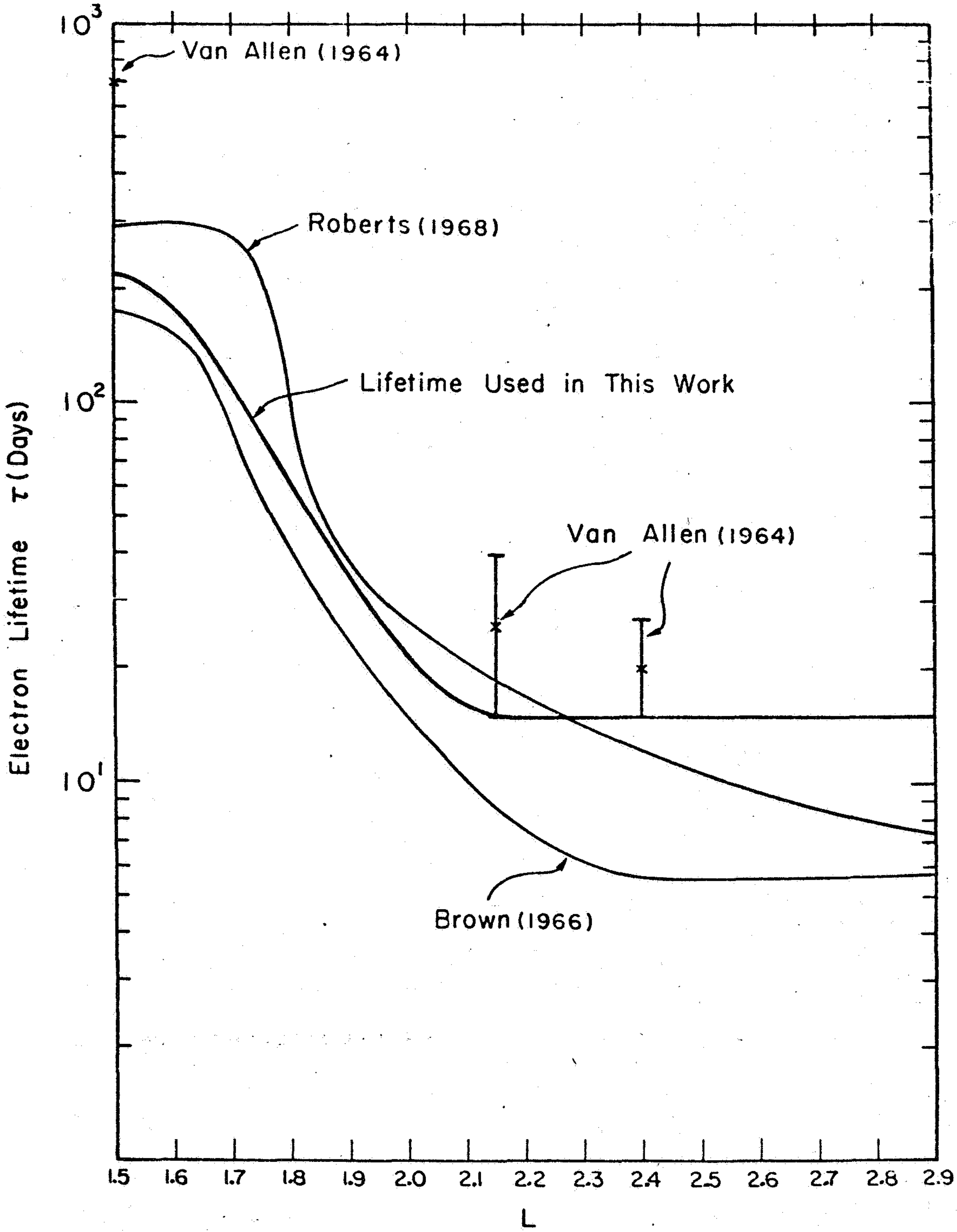

Figure 4. Electron Pitch-Angle Diffusion Lifetimes

For this study the eight-week time period was subdivided into ten time intervals of five or six days each. Five time periods (days 220-225, 225-230, 230-235, 235-240 and 240-245) precede the geomagnetic storm. No data is available from 246.8 to 249.6, a period which includes some of the main phase and much of the recovery phase of the storm. Five others (250-255, 255-260, 260-265, 265-270 and 270-275) follow the storm. With ten time periods, ten L values and four values of the first invariant there are 400 possible computations of the diffusion coefficient from equation 3. Missing or broken data, due in part to the limited differential energy range of the instrument, confined the actual determinations to 157 calculated values.

The important increase which took place within the period of day 246.8 to day 249.6 cannot be studied because there is no data for the period. According to Williams et al. (1968) a storm with a D_{st} value of -182γ may be expected to add electrons (by a mechanism not yet known) to L shells as low as 3.0. Whether this storm added new electrons to L shells lower than suggested by the D_{st} value, or whether enhanced radial diffusion is responsible, cannot be established in this case.

5. Results

The solution of equation 3 requires that the value of m be known. The first calculations of the radial diffusion coefficient were done with the assumption that m is 10, but the resulting values of D showed a seventh power variation, a result inconsistent with the assumption. Systematic reduction of m produced increasing values of the resulting power law coefficient until agreement was reached at m of 7.9, thus determining the proper value of m to be used in the calculations of D.

Representative results for the radial diffusion coefficient D as a function of time are shown in Figure 5. This particular example shows an important characteristic of the results which appear at all four values of the first invariant and at all L values within the range of the investigation: the diffusion coefficients for post-storm periods do not differ significantly from those for the pre-storm period. Because no significant variations with time appear in these coefficients, all of them have been averaged together at each L value. These averaged values are shown in Figure 6. The ends of the error bars representing possible systematic errors due to the choice of pitch angle lifetime have also been averaged and included in Figure 6. As a rough average, the error bars extend 25% above and below the values corresponding to the selected pitch angle lifetimes, and thereby indicate the sensitivity of the results to the choice of τ.

A tendency toward smaller coefficients at higher values of the first invariant is apparent. If the diffusion coefficient is assumed to be of the form $D = a\, L^m \mu^n$, then a two dimensional least squares fit to the logarithms of D gives the result

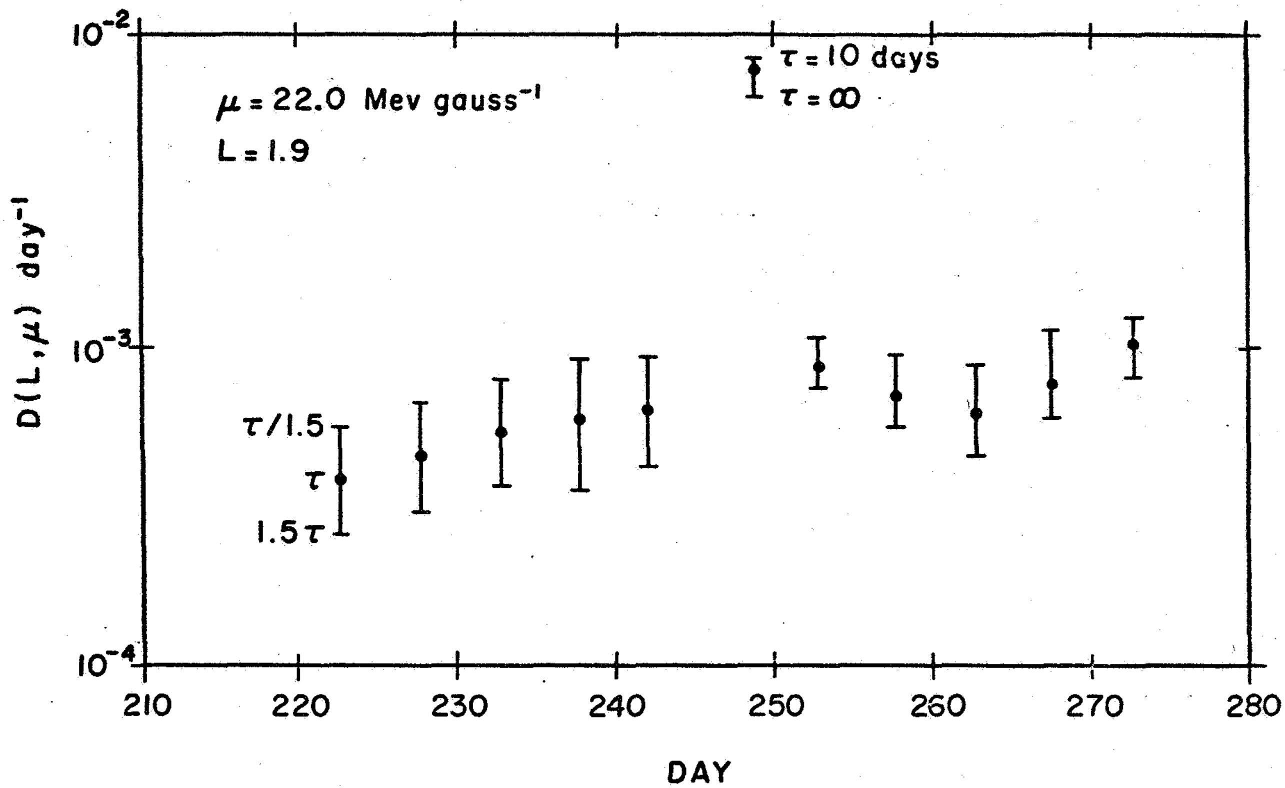

Figure 5. Representative Values of the Required Radial Diffusion Coefficient at Fixed L and First Invariant

Systematic error bars represent the resulting range in D when the pitch angle lifetime is varied a factor of 1.5 above and below the values used for the points, which are given in Fig. 4.

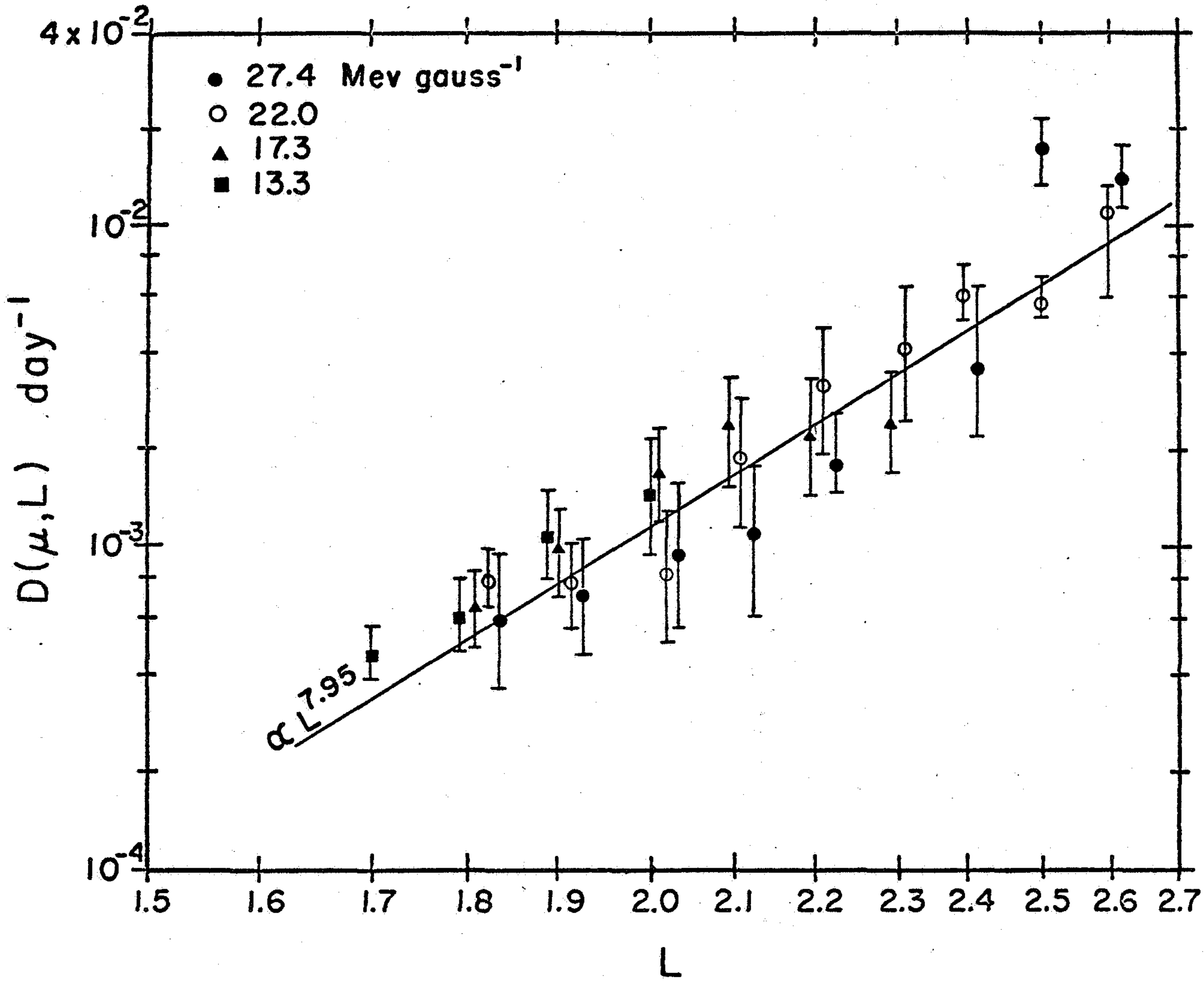

Figure 6. Radial Diffusion Coefficients Calculated from Eq. (3) Averaged Over All Time Periods at Each L

The calculations correspond to increments of 0.1 in L. Slight L displacements have been used in the plot for clarity.

$$D = 2.7 \times 10^{-5} L^{7.9} \mu^{-0.5} \text{ day}^{-1} \qquad (4)$$

The standard deviation of these data from the power law fit is 26 percent.

Discussion

1. Mechanism of Inner Zone Electron Repopulation

The September 1966 electron redistribution which has been quantitatively analyzed in this paper was reported by Pfitzer and Winckler (1968) to be the first intrusion of natural electrons deep into the inner zone after the Starfish nuclear injection of 1962. Their report interpreted this event as an example of inward radial diffusion. Farley (1969) studied the role of radial diffusion in the gradual disappearance of the Starfish electrons and noted that by September, 1966 the decay had proceeded so far that the average radial gradient of the adjusted density ($L^2 f$) between the inner and outer zone was positive, and therefore electrons might be expected to diffuse inward from the outer zone with a radial electron current given by

$$I = \frac{D}{L^2} \frac{\partial (L^2 f)}{\partial L}$$

The inner and outer electron zones are separated by the slot region (approximately $2.5<L<3.5$) in which electron pitch angle lifetimes are less than the average interval between major magnetic storms. The slot region is consequently empty of energetic electrons during quiet periods, and electrons diffusing inward from the outer zone are normally lost by pitch angle diffusion in the slot.

In major magnetic storms, such as the one of September 1966, important additions are made to the outer zone electron population by as yet unknown mechanisms. It is possible that some direct additions are made to L values within the inner zone, although the results of Williams et al. (1968) indicate that this probably does not happen in a storm of the intensity of the one of September 2, 1966. The radial gradient of L^2f, and consequently the inward radial electron current, is much enhanced. Electrons diffuse into and fill the slot region, spilling over into the inner zone where electron lifetimes are very long ($\sim$ one year). Within several weeks pitch angle diffusion removes the electrons in the slot, leaving the inner zone electrons in orbits of long lifetime. These inner zone electrons are slowly lost by inward diffusion toward the earth, outward diffusion into the slot, and by collisions with atmospheric constituents. Farley (1969) estimated from rough arguments that a diffusion coefficient of 8×10^{-4} day^{-1} would be required to cause the diffusion observed after the September 1966 storm, and this estimate is borne out by the quantitative results of this paper.

Although it is possible that the diffusion coefficient may have been temporarily elevated during the main phase of the storm, the observed redistribution took several weeks, and the results of this work indicate that the diffusion coefficient during this period does not differ significantly from its pre-storm value. The redistribution continued because of the larger gradients in $L^2 f$, and consequently larger diffusion currents, produced by the geomagnetic storm.

2. The Role of Radial Diffusion in the Radiation Belts

Attempts to account for the existence or time evolution of various particle distributions in the radiation belt by including a radial diffusion mechanism are now rather numerous. Figure 7 includes most of the diffusion coefficients which have resulted when a diffusion term equivalent to that in equation 3 has been employed. Two other values discussed previously by one of us (Farley, 1968) have been omitted. Even when due allowance is made for the uncertainties which enter because of the wide variety of approximations in data and techniques which have been employed by various authors, it is apparent that these results, plotted in this way, do not lend much support to the existence of the radial diffusion mechanism. However, an appropriate review of the underlying theory suggests that a different method of comparison among these values will be more revealing.

Radial diffusion may be driven either by magnetic field variations, or by electric field variations. Fälthammar (1968) has assumed a magnetic disturbance field which contains only the zero and first order terms in a spherical harmonic expansion, and obtains the result that the magnetic diffusion coefficient will have the value

$$D_M \sim \Gamma(\alpha_o) L^{10} \left[\nu^2 P(\nu)\right]_{\nu=\frac{1}{\tau_d}}$$

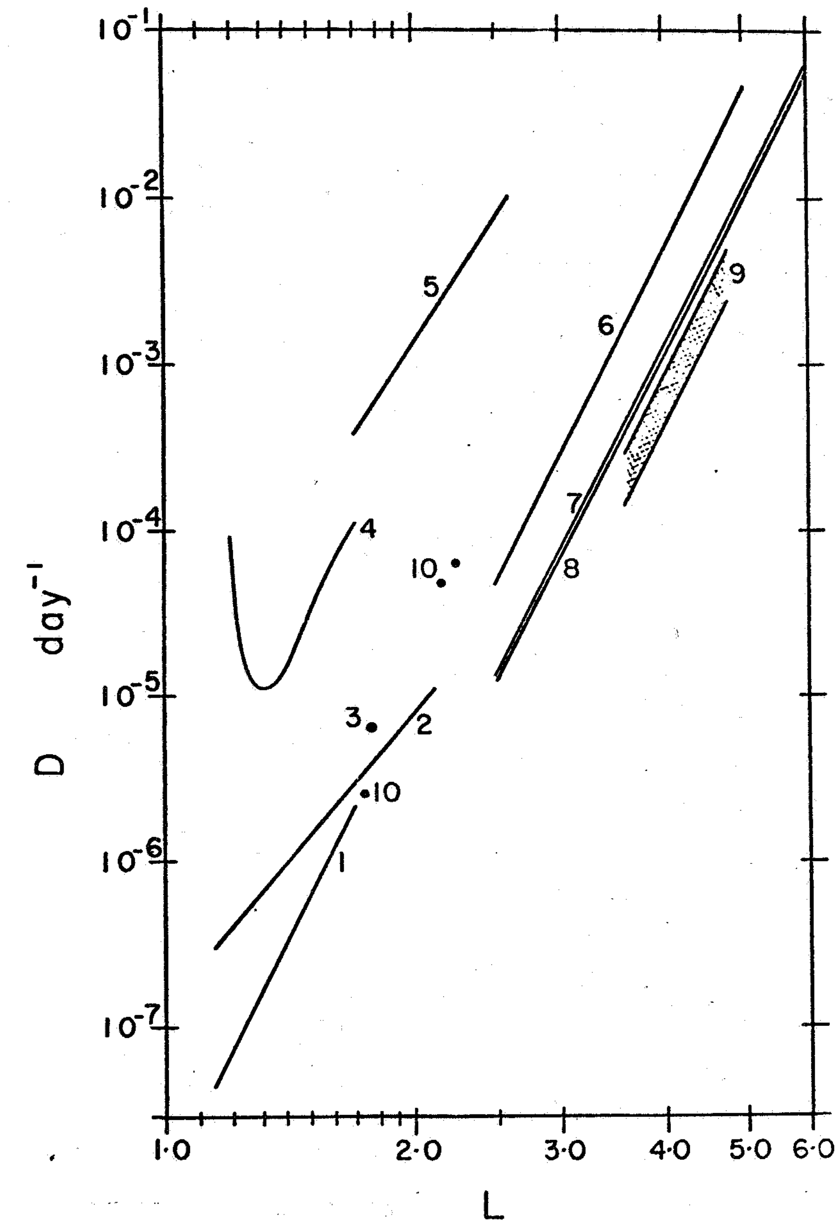

Figure 7. Previously Reported Radial Diffusion Coefficients

(1) Farley, et al., 1971, inner zone energetic protons; (2) DeForest, 1970, inner zone energetic protons; (3) Newkirk and Walt, 1968, artificial electrons; (4) Farley, 1969, Starfish electrons; (5) Present results from natural electrons; (6) Newkirk and Walt, 1968, outer zone electrons; (7) Nakada and Mead, 1965, outer zone protons; (8) Söraas, 1969, outer zone protons; (9) Lanzerotti et al., 1970, outer zone electrons; (10) Walt, 1971, artificial electrons.

where $P(\nu)$ is the power spectrum of the disturbance amplitude, τ_d is the particle drift period and Γ is a function which is unity for equatorially trapped particles ($\alpha_o = 90^o$) and decreases by about an order of magnitude for particles with small pitch angles. For a magnetic power spectrum which decreases as the square of the frequency, this result predicts a diffusion coefficient proportional to the tenth power of L and independent of particle drift period. A number of the results included in Figure 7 have approximately this L variation, although the proportionality constant varies from something like 5×10^{-10} day^{-1} up to 1×10^{-8} day^{-1}. Clearly, the results of the present paper do not fall into this group.

Fälthammar (1965, 1966) has also computed that variations of an electric potential field will produce diffusion with a coefficient given by

$$D_E = \frac{1}{8B_o{}^2} \left[\sum_{n=1} P_n \; (L,\nu) \right]_{\nu=\frac{n}{\tau_d}} \tag{5}$$

where $B_o(L)$ is the equatorial magnetic dipole field and P_n is the power spectrum of the time variation of the nth spatial Fourier coefficient of the electric potential field in the equatorial plane. This coefficient is independent of the particle pitch angle.

Cornwall (1968) has applied this result to the electrostatic fields which drive the currents that produce magnetic bays. Using only the first term in the expansion (which is the azimuthal component of a uniform electric field across the magnetosphere), Cornwall obtains the result

$$D_E = \frac{c^2 T\ E^2(L)}{4B_o^2} \left[1 + \left(\frac{\pi T}{\tau_d}\right)^2\right]^{-1} \qquad (6)$$

where T is the characteristic time of magnetic bays (2000 seconds) and E is assumed to be 1 to 10 kilovolts across several earth radii. The equation is to be evaluated in cgs units.

A certain amount of recent experimental evidence now indicates that there are large-scale electric fields within the plasmapause, although the observations are not sufficiently extensive to permit the electric field to be decomposed into the amplitude and time variation of each spatial Fourier component which is required for a formal evaluation of equation 5.

In particular, Mozer (1971) has made balloon measurements which indicate a high-altitude electric field of 0.6 mv per meter. These measurements are difficult to make, and it is uncertain to what extent local ionospheric fields may be included in these measurements.

The observations of Carpenter (1971) of the radial motion of whistler ducts appear to be more directly applicable in the evaluation of the radial diffusion coefficient due to electric field variation, since these measurements can be accounted for only by magnetospheric electric fields within the plasmapause. Carpenter's observations of the duct motion, which have been chiefly on the nightside of the earth, reveal the azimuthal component of this electric field. The observations indicate that this field extends to an L at least as low as 2.7. No data is available at smaller L values. The fields are substorm associated, and are sometimes directed eastward and sometimes westward. The amplitude, at least during substorm periods, may vary from 0.2 to 0.6 mv per meter. While frequency spectrums of the spatial Fourier components have not been obtained, the observations indicate substantial fluctuations of these fields with periods of the order of a half hour.

In order to compare the diffusion coefficient of this paper (equation 4) with the one to be expected from electric field variations, the drift period has been computed for the particles represented by each data point in Figure 6 from the relation

$$\tau_d = \frac{2\pi e R_e^2 L^2}{3\mu c} \left[1 + \frac{2\mu B_o}{m_o c^2} \right]^{1/2}$$

This relation must be evaluated in cgs units. A best fit of these data to equation 6 has been made, allowing the electric field amplitude E and period T to vary simultaneously. The best fit is found for E = 0.28 mv per meter and T = 1600 seconds, so that

$$D_E = 6.82\text{x}10^{-5}\ L^6 \left[1 + \left(\frac{\pi T}{\tau_d}\right)^2 \right]^{-1} \text{day}^{-1} \qquad (7)$$

The standard deviation of our data from equation 7 is 32 percent, almost as good as the power law fit in L and μ. This is not to say that the data points which constitute the results of this paper will fit a function very different from the power law fit of equation 4. Rather, the reasonably good fit occurs because equation 6 is approximately a power law when transformed to the variables L and μ over the limited range of these variables in this study.

The diffusion coefficients calculated in this paper thus appear to fit the predictions of a simplified electric field variation theory with values of the electric field E and characteristic period T which are consistent with the limited available experimental evidence. In a recent paper, Cornwall (1971) found that equation 7 with the numerical factor in the range 3×10^{-5} to 1×10^{-4} gave a radial diffusion coefficient which enabled him to predict alpha to proton rations within the magnetosphere in reasonable agreement with measurements. The very close agreement between his value and equation 7 supports the validity of diffusion driven by electric field variations. While more detailed electric field information is desirable so that the more sophisticated theory may be employed, the agreement already obtained permits the conclusion that electric field variations are probably responsible for most of the observed diffusion and subsequent repopulation of the inner radiation zone by electrons.

It has been noted by Roederer and Schulz (1971) that radial diffusion coupled to pitch angle diffusion can be produced by the shell splitting caused by a static electric field. The diffusion coefficient for this process has been computed at L of 2 for 1 Mev electrons and a .28 mv per meter electric field, using their theoretical result. The coefficient thus calculated is several orders of magnitude smaller than the one obtained in this work, indicating that diffusion by electric field variations is the more important process in this event.

It is now apparent why comparisons among calculated coefficients like that of Figure 7 are not appropriate. The theories for both D_M and D_E predict that these coefficients will be functions of L and τ_d, and therefore particles at the same L will not experience the same diffusion unless they have the same drift period. Only in the very special case of diffusion driven by magnetic field variations with a power spectrum falling as ν^{-2} will the coefficient be independent of drift period.

A more general approach to comparison of reported results is to compute the ratio of the experimental values to the theoretical predictions with suitable (i.e., experimental) values of the amplitudes of the field variations. In general, diffusion may be driven by both electric and magnetic variations so that

$$D_T = D_E + D_M \tag{8}$$

For these comparisons it has been assumed that D_E is given by equation 7, and that the magnetic coefficient has the value

$$D_M = 1\text{x}10^{-8}\ \bar{\Gamma}\ L^{10}\ \text{day}^{-1} \tag{9}$$

This choice for D_M, which implies a power spectrum falling as ν^{-2}, is largely based on the findings of <u>Farley and Walt</u>, (1971), which are applicable to high energy inner zone protons. The calculations of <u>Nakada and Mead</u> (1965) of the diffusion coefficient due to magnetic impulses and sudden commencements resulted in a value $1.55\text{x}10^{-10}\ L^{10}\ \text{day}^{-1}$, a result too small to account for the observed diffusion of any population of trapped particles. Evidently other time-varying magnetic phenomena must contribute if magnetic diffusion is important. $\bar{\Gamma}$ is the suitably averaged value of the pitch angle dependence of the magnetic diffusion coefficient, and depends upon the range of pitch angles included in the flux measurements. For equatorially trapped particles $\bar{\Gamma}=1$; for an outer zone (isotropic) pitch angle distribution measured with an omnidirectional detector, $\bar{\Gamma}=0.48$; for a typical inner zone pitch angle distribution measured with an omnidirectional detector, $\bar{\Gamma}=0.71$.

The ratio of the experimental values to D_T has been plotted in Figure 8. Labels E and M have been placed on the curves to indicate whether D_E or D_M is the principal contributor to the theoretical coefficient when D_E and D_M have the values given by (7) and (9) respectively. From an examination of

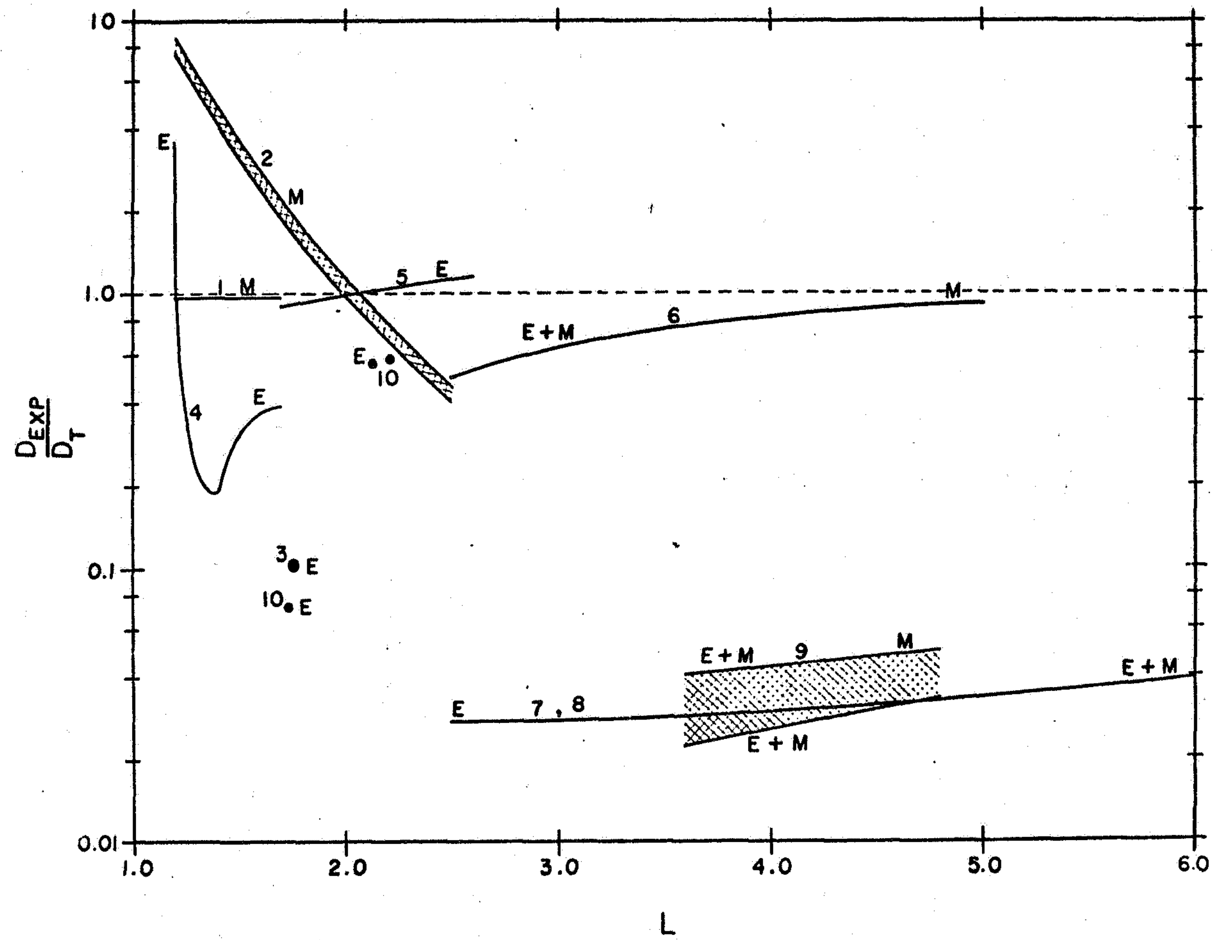

Figure 8. Ratio of Previously Reported Radial Diffusion Coefficients to the Theoretical Coefficient as Defined by Eq. (8)

E, M, or E + M indicates whether the electric term, the magnetic term, or neither dominates the theoretical expression when D_E and D_M are given the values in Eqs. (7) and (9), respectively. Identifications are as given in Fig. 7.

Figure 8, it is evident that magnetic diffusion is dominant only for the high energy trapped protons of the inner zone (curves 1 and 2) when D_E and D_M are given the values in equations 7 and 9, respectively. This results from the short drift period of these protons, which makes D_E small. Magnetic diffusion also becomes important for the largest values of L for several of the particle populations (curves 6-9) in Figure 8 because its L dependence is stronger than that of electric diffusion. Clearly, different choices for the parameters in D_M will not bring significantly better agreement among the reported values compared in Figure 8. If a smaller value is selected for D_M, only curves 1 and 2 of Figure 8 will be affected in an important way since D_E largely determines the position of the other curves already. If a larger value is selected for D_M, curves 1 and 2 will no longer indicate agreement, while the situation in the outer zone becomes worse since three of the experimental values are already substantially below D_T.

Several general comments may be made concerning this comparison. There is a group of six inner zone measurements which, together with the Newkirk and Walt outer zone measurement, are in reasonable agreement with D_T as far as their magnitude is concerned. Their L variations tend to be somewhat different, in general. In some cases this may be due to the solution technique employed, or the limited range of L in a particular determination. In particular, the diffusion coefficient has been assumed to have a power law variation in L, μ coordinates in many of these calculations (including the present work). Naturally, those who have assumed a power law have obtained that result. The theory does not predict such a variation except in special cases, although a power law may be a reasonable representation over a restricted range in L.

The two inner zone points which are clearly in disagreement with D_T were determined from the spreading of the artificially injected electrons of the USSR nuclear test of November 1, 1962 and those from one of the US Argus tests. The other two points at somewhat larger L in the inner zone are from the other two Argus tests, and they are in better agreement with D_T.

The steep radial gradient of the distribution function and the many determinations of its shape during the decay of the electrons from the USSR test make the point at L of 1.76 one of the more reliable determinations. From qualitative observations of these injected electrons, it seemed possible to predict that inward radial diffusion could not populate the inner zone. Since it is one conclusion of this paper that radial diffusion does indeed repopulate the inner zone, the period of decay of the electrons from the USSR test and from one of the Argus tests may have been unusually quiet. These artificial electron populations did have one feature unique among all other populations from which diffusion coefficients have been calculated: they consisted primarily of electrons mirroring at low altitudes during the early period in which the diffusion coefficients were computed. However, the theory shows that D_E has only a weak dependence on particle pitch angle through τ_d and it is not otherwise apparent how the pitch angle distribution might be important to the problem.

In addition to these inner zone values, there exists a group of three outer zone values which are smaller than D_T by factors varying from 20 to 50. It is the departure of these values from D_T which represents the largest discrepancy between experiment and the theory which has been assumed to apply. One of these results (Lanzerotti et al., 1970) represents an additional determination of the diffusion coefficient for the same event studied by Newkirk and Walt, although applicable to somewhat different particle energies, L ranges, and time periods. The reasons for this discrepancy and the relative merits of the techniques for obtaining D have been adequately debated elsewhere (Walt and Newkirk, 1971; Lanzerotti et al., 1971).

The reported values of Nakada and Mead (1965) and Söraas (1969) both suffer from an error in which the factor μ^{-1} in equation 2 was omitted when conversion was made from measured flux to the required distribution function. It is not likely that this will produce an error in D of a factor 20 to 50.

Present theories postulate that the magnetic and electric fields whose fluctuations produce radial diffusion are comparable in scale to the size of the magnetosphere, and there are no obvious reasons why inner or outer zone values should not be predictable from the same theory. It is possible that some or all of the apparent discrepancies may be resolved by the discovery of more localized field fluctuation phenomena, or by determination of the actual time variations of large-scale fluctuation phenomena.

Conclusions

1. The inner radiation zone is repopulated with electrons during and after large magnetic storms. Electrons accelerated in or transported to the outer radiation zone during the active period of the storm diffuse radially inward across the normally empty slot region and reach the inner zone, where trapped electron lifetimes are very long.

2. The diffusion coefficient required to drive this diffusion is consistent with that which would result from variations of a large-scale electric field across the magnetosphere and within the plasmapause, extending to an L at least as low as 1.7. The required magnitude and characteristic period are 0.28 mv per meter and 1600 seconds, respectively. These values are in rough agreement with limited experimental observations.

3. If the values given above for the electric field amplitude and time variation are correct and appropriate for the entire magnetosphere, then the radial diffusion of all particle populations studied thus far, with the exception of the high-energy inner zone protons, is strongly affected by these electric field variations. The high energy protons, because of their

short drift periods, are little affected by electric field variations whose period is 1600 seconds. Their diffusion must be due to magnetic variations (as assumed in the foregoing discussion) or to as yet unreported electric field variations of shorter periods.

4. A review and comparison of previously published radial diffusion coefficients results with predictions of the simple theory indicate an area of general agreement on the magnitude of the coefficient in the inner radiation zone, at least when reasonable allowance is made for possible uncertainties in data and techniques, as well as some allowance for time variation of the diffusion process. A group of outer zone measurements cannot be reconciled with the other measurements using the simple theory, leaving an important discrepancy for both theoretical and experimental study.

References

Brown, W.L., Observations of the transient behavior of electrons in the artificial radiation belts, in Radiation Trapped in the Earth's Magnetic Field, edited by B.M. McCormac, p. 610, D. Reidel Publishing Co., Dordrecht, Holland, 1966.

Carpenter, D.L., Keppler Stone, Jan C. Siren, and T.L. Crystal, Magnetospheric electric fields deduced from drifting whistler paths, submitted to J. Geophys. Res., 1971.

Cornwall, J.M., Diffusion processes influenced by conjugate point wave phenomena, Radio Science, 3, 740, 1968.

Cornwall, John M., Radial diffusion of ionized helium and protons: a probe for magnetospheric dynamics, J. Geophys. Res., in press, 1972.

DeForest, S.E., Long term variations in high-energy geomagnetically trapped particles, Ph.D. dissertation, Department of Physics, University of California, San Diego, July, 1970.

Fälthammar, C.-G., Effects of time dependent electric fields on geomagnetically trapped radiation, J. Geophys. Res., 70, 2503, 1965.

Fälthammar, C.-G., Coefficients of diffusion in the outer radiation belt, in Radiation Trapped in the Earth's Magnetic Field, edited by B.M. McCormac, p. 398, D. Reidel Publishing Co., Dordrecht, Holland, 1966.

Fälthammar, C.-G., Radial diffusion by violation of the third adiabatic invariant, in Earth's Particles and Fields, edited by B.M. McCormac, p. 157, Reinhold Book Corporation, New York, N.Y., 1968.

Farley, T.A., Radial diffusion of electrons at low L values, J. Geophys. Res., 74, 377, 1969.

Farley, T.A., Radial diffusion of Starfish electrons, J. Geophys. Res., 74, 3591, 1969.

Farley, T.A., and Martin Walt, Source and loss processes of protons of the inner radiation belt., J. Geophys. Res., 76, 8223, 1971.

Lanzerotti, L.J., C.G. Maclennan, and Michael Schulz, Radial diffusion of outer-zone electrons: an empirical approach to third-invariant violation, J. Geophys. Res., 75, 5351, 1970.

Lanzerotti, L.J., C.G. Maclennan, and Michael Schulz, Reply to "comments on 'Radial diffusion of outer-zone electrons'", J. Geophys. Res., 76, 5371, 1971.

Lyons, Lawrence R., Richard Mansergh Thorne, and Charles F. Kennel, Pitch-angle diffusion of radiation belt electrons within the plasmasphere, submitted to J. Geophys Res., 1971.

Mozer, F.S., Power spectra of magnetospheric electric field, J. Geophys. Res., 76, 3651, 1971.

Nakada, M.P., and G.D. Mead, Diffusion of protons in the outer radiation belt, J. Geophys. Res., 70, 4777, 1965.

Newkirk, L.L., and M. Walt, Radial diffusion coefficient for electrons at $1.76<L<5$, J. Geophys. Res., 73, 7231, 1968.

Pfitzer, K.A., and J.R. Winckler, Experimental observation of a large addition to the electron inner radiation belt after a solar flare event, J. Geophys. Res., 73, 5792, 1968.

Roberts, C.S., Cyclotron-resonance and bounce-resonance scattering of electrons trapped in the earth's magnetic field, in Earth's Particles and Fields, edited by B.M. McCormac, p. 317, Reinhold Book Corporation, New York, 1968.

Roederer, Juan G., and Michael Schulz, Splitting of drift shells by the magnetospheric electric field, J. Geophys. Res., 76, 1055, 1971.

Söraas, F., Comparisons of post-storm non-adiabatic recovery of trapped protons with radial diffusion, GSFC Report X-619-69-241, 1969.

Vampola, A.L., Energetic electrons at latitudes above the outer-zone cutoff, J. Geophys. Res., 74, 1254, 1969.

Vampola, A.L., Natural variation in the geomagnetically trapped electron population, Aerospace Technical Report, TR-0095(6260-20)-17, 1971.

Van Allen, J.A., Lifetimes of geomagnetically trapped electrons of several Mev energy, Nature, 203, 1006-1007, 1964.

Van Allen, J.A., Spatial distribution and time decay of the intensities of geomagnetically trapped electrons from the high altitude nuclear burst of July 1962, in _Radiation Trapped in the Earth's Magnetic Field_, edited by B.M. McCormac, p. 575, D. Reidel Publishing Company, Dordrecht, Holland, 1966.

Walt, M., and L.L. Newkirk, Comments on 'Radial diffusion of outer-zone electrons', _J. Geophys. Res._, _76_, 5368, 1971.

Walt, M., Radial diffusion of trapped particles and some of its consequences, _Rev. of Geophys._, _9_, 11, 1971.

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13. ABSTRACT

A quantitative study of the intrusion of natural electrons into the inner radiation zone during and after the geomagnetic storm of September 2, 1966 shows that the transport is consistent with a radial diffusion mechanism in which the first two invariants are conserved. Except for the three day period of the storm main phase when data were missing, the radial diffusion coefficient is $D = 2.7 \times 10^{-5} L^{7.9} \mu^{-0.5}$ day^{-1}, in the range $1.7 \leq L \leq 2.6$ and $13.3 \leq \mu \leq 27.4$ Mev gauss^{-1}. This value could be produced by variation of a large-scale electric field across the magnetosphere having an amplitude of 0.28 mv per meter and a period of 1600 seconds. Electric fields having approximately these characteristics have been inferred from previous observations of the motion of whistler ducts within the plasmapause. If fields of this amplitude and period exist throughout the magnetosphere, the radial diffusion of all geomagnetically trapped particles except the high energy inner zone protons is strongly influenced by electric field variations. A comprehensive review of previously reported radial diffusion coefficients shows reasonable agreement for L less than about 3.0, but serious discrepancies among reported values exist for determinations made in the outer zone. These discrepancies cannot be explained by the simple theory of radial diffusion due to variation of large-scale electric or magnetic fields.

14\. KEY WORDS

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